6 HUMAN PERFORMANCE AND SCANNING SENSITIVITY

6.1 Introduction

Scanning is performed during radiological surveys in support of decommissioning to identify the presence of any locations of elevated direct radiation. The probability of detecting residual contamination in the field is affected not only by the sensitivity of the survey instrumentation when used in the scanning mode of operation, but also by the surveyor's ability. The surveyor must decide whether the signals represent only the background activity, or whether they represent residual contamination in excess of background.

The minimum detectable concentration of a scan survey (scan MDC) depends on the intrinsic characteristics of the detector (efficiency, window area, etc.), the nature (type and energy of emissions) and relative distribution of the potential contamination (point versus distributed source and depth of contamination), scan rate and other characteristics of the surveyor. Some factors that may affect the surveyor's performance include the costs associated with various outcomes—e.g., cost of missed contamination versus cost of incorrectly identifying areas as being contaminated —and the surveyor's *a priori* expectation of the likelihood of contamination present. For example, if the surveyor believes that the potential for contamination is very low, as in an unaffected area, a relatively large signal may be required for the surveyor to conclude that contamination is present. NUREG/CR-6364, "Human Performance in Radiological Survey Scanning," provides a complete discussion of the human factors as they relate to the performance of scan surveys.

Scanning sensitivities are often empirically determined, depending on the experience of the surveyor. In fact, Lee and Tritch (DOE 1994) state that due to the many factors affecting scan sensitivity, the scan MDC using a particular instrument and survey technique would best be determined experimentally. While empirically determined scan MDCs provide one technique, the resources necessary to implement this option may be burdensome. The approach described in this report to determine the scan sensitivity involves several steps, resulting in an expression for scan MDCs in terms of measurable surface activities and soil concentrations. An overview of the process used to determine scan MDCs is given below.

Signal detection theory provides a framework for the task of deciding whether the audible output of the survey meter during scanning was due to background or signal plus background levels. An index of sensitivity (d') that represents the distance between the means of the background and background plus signal, in units of their common standard deviation, can be calculated for various decision errors—Type I error (α), and Type II error (β). As an example, for a correct detection or true positive rate of 95% (1-β) and a false positive rate (α) of 5%, d' is 3.29 (similar to the static MDC in Section 3 for the same decision error rates). The index of sensitivity is independent of human factors, and therefore, the ability of an ideal observer (theoretical construct), may be used to determine the minimum d' that can be achieved for particular decision errors. The ideal observer makes optimal use of the available information to maximize the percent correct responses, providing an effective upper bound against which to compare actual surveyors. Computer simulations and field experimentation can then be performed to evaluatethe surveyor efficiency (p) relative to the ideal observer. The resulting expression for the ideal observer's minimum detectable count rate (MDCR), in counts per minute, can be written

$$MDCR = d' * \sqrt{b_i} * (60/i) = s_i * (60/i) \tag{6-1}$$

where

MDCR = minimum detectable (net) count rate in counts per minute, can be written
b_i = background counts in the observation interval,
s_i = minimum detectable number of net source counts in the observation interval, and
i = observational interval (in seconds), based on the scan speed and areal extent of the contamination.

Scan MDCs are determined from the MDCR by applying conversion factors to obtain results in terms of measurable surface activities and soil concentrations. The theoretical framework for assessing human performance during radiological scans is more fully developed in the companion document NUREG/CR-6364. As an example, the scan MDC for a structure surface can be expressed as

$$Scan\ MDC = \frac{MDCR}{\sqrt{p}\ \epsilon_i\ \epsilon_s\ \frac{probe\ area}{100\ cm^2}} \tag{6-2}$$

6.2 Review of Scanning Sensitivity Expressions and Results

One common expression for scanning sensitivity is based on the surveyor being able to detect three times the background level for low count rates (NUREG/CR-5849). However, experience shows that at background count rates of thousands of counts per minute, an increase of 25-50% is readily detected (DOE 1992). This reduction in the detectable level above background reflects the expected relationship of detectability as a function of the square root of the background rate (refer to static MDC expression in Section 3).

The specification of detectable levels is complicated by the difficulty of defining “detectable” as applied to the performance of the surveyor. For example, guidance on scanning capabilities is given in draft ANSI Standard 13.12, “Control of Radioactive Surface Contamination on Materials, Equipment, and Facilities To Be Released for Uncontrolled Use.” This document states that the scanning speed shall be slow enough to ensure that a small-diameter source is detected with a 67% probability. However, the specification of scan MDC requires a policy regarding false positives as well; note that the familiar static MDC equations typically use a false positive rate of 5%. In theory, any correct detection rate can be achieved for any source intensity if the number of false positives permitted is unlimited.

A few attempts to quantify scanning sensitivity experimentally have been reported. Scanning MDCs have been evaluated for both alpha and beta instrumentation under varying background conditions using a semi-empirical approach (Goles et al. 1991). MDCs were defined as that activity that could be detected 67% of the time under standard survey conditions. The instruments evaluated were, for alpha detection, a 50-cm^2 portable alpha monitor, a 100-cm^2 large-area scintillation monitor, and a 100-cm^2 gas proportional counter; for beta/gamma detection, a pancake GM probe, a 100-cm^2 large-area scintillation monitor, and a 100-cm^2 gas proportional counter. The test procedure involved maintaining a scan rate of 5 cm/s, with a scan height held at 0.64 cm. Alpha sources were 2.54-cm-diameter, electroplated sources; beta/gamma sources consisted of point source geometries and uniformly dispersed geometries. The MDC for alpha activity was defined as the amount of activity that produces one count as the detector passes over the surface (alpha background was considered to be zero) and the MDC for beta/gamma activity was determined for different background activities (e.g., 50, 250, and 500 cpm), based on whether it could be detected 67% of the time. For the most part, the researchers concluded that detectors were more sensitive to point sources than to areal sources. The reported scanning sensitivities for the GM detectors demonstrated that activities producing net instrument responses of 305, 310, and 450 cpm could be statistically recognized 67% of the time in 50-, 250-, and 500-cpm background fields, respectively. Goles et al. (p. 4d) cautioned that the “data are highly idealized, and that the performance of these instruments may differ considerably under field conditions.”

Sommers (1975) obtained experimental data to check the validity of the theoretical calculations of source detection frequency. Calibrated sources were moved past the detector windows to determine source detection frequencies for various velocities (ranging from 2.4 to 15 cm/s), and source-detector distances in a background of 120 cpm. The experimental results are averages over 100 observations per datum point from two or more experienced surveyors. The effects of varying instrument time constants, probe velocity, and background activities on source detection frequencies (in percent) were plotted. The researcher concluded that source detection frequencies were strongly dependent on source strength, survey velocity, background activity, detector sensitivity, and the time constant of the survey meter. At scanning speeds of 10 to 15 cm/s, a source strength of 10,000 to 15,000 betas/min was required to provide a detection frequency of 90%. It was also determined that “with small diameter sources emitting 5,000 betas/min, source detection frequency at 120 counts/min background is about 80% using the speaker outputs, regardless of the survey velocities between 3.5 and 15 cm/s” (Sommers, p. 760).

In LA-10729, Olsher et al. determined the scanning sensitivity of alpha detection instrumentation by measuring the hot spot detection frequency under realistic survey conditions. The procedure involved more than 40 surveyors with varying levels of experience, who were asked to survey five stations, each consisting of a 4-foot x 4-foot section of masonite that was painted with a Th-232-based paint. The thorium-based paint, which was the same color as the original paint and thus hid the hot spots, was applied to nine locations at each station. The alpha activity levels ranged from 64 to 672 dpm. The surveyors were instructed to survey each of the five stations and to record their results on a survey grid map. The detection frequency and false positive frequency were determined for each survey group. The alpha source activity for a 50% detection frequency ranged from 392 to 913 dpm for the ZnS scintillation detectors evaluated. One interesting result of this evaluation was that less-experienced surveyors had a higher detection probability than did experienced surveyors. The authors attributed this to the fact that the inexperienced surveyors took approximately twice as long to complete the scan survey.

Lastly, in a radiation detection experiment performed by 25 health physics technicians, Thelin obtained experimental data to evaluate the scan MDC for a portable scintillation detector (Thelin

1994). Eight sources were randomly placed against the inner surface of a box with approximate dimensions 46 × 36 × 30 cm. The source levels ranged from 236 to 1516 net cpm. The technicians were asked to scan the outside of the box and to identify locations that have higher count rates than the box background. The number of sources identified by each technician was evaluated and a hyperbolic function was fit to the experimental data. Thelin reports that at a background count rate of 482 ± 52 cpm at 2 sigma, the technicians were able to locate and identify source levels of 700 cpm approximately 90% of the time.

6.3 Signal Detection Theory

Signal detection theory provides a means for characterizing the performance of surveyors performing scans. The theory relies on the statistical decision techniques derived in Section 3 and applies to the detection of signals in background noise by surveyors. Personnel conducting radiological surveys for residual contamination at decommissioning sites must interpret the audible output of a portable survey instrument to determine when the signal ("clicks") exceeds the background level by a margin sufficient to conclude that contamination is present. It is difficult to detect low levels of contamination because both the signal and the background vary widely.

In abstract terms, the task of personnel conducting radiological scan surveys can be briefly characterized as follows. The condition of the surface being scanned is represented to the surveyors by samples from random processes (Poisson distributed counts). Furthermore, the samples are limited in size (i.e., time constraint depending on scan speed) for practical reasons. On the basis of the samples, the surveyors must decide whether they have sampled the distribution of activity associated with a contaminated surface or an uncontaminated surface (background only). The concepts and methods of signal detection theory are well suited to the analysis of performance on such tasks, and require the specification of the acceptable Type I and Type II error rates. NUREG/CR-6364 describes signal detection theory in greater detail.

The information available to the observer can arise from either noise alone or from signal-plus-noise and can be represented by two (typically overlapping) probability density distributions (Figure 6.1). The task of the observer is to indicate whether an increase in survey instrument output arose from a "noise alone" or a "noise plus signal" event. To make this decision, a criterion must be established at some point along the continuum—e.g., once the criterion point is set, any measurement greater (to the right) than the criterion will be interpreted as contamination. If the underlying distributions can be assumed to be normal and of equal variance, an index of sensitivity (d') can be calculated which represents the distance between the means of the distributions in units of their common standard deviation. The index is calculated by transforming the true positive and false positive rates to standard deviation units, i.e., z-scores (Egan 1975, p.61) and taking the difference:

$$d' = z\,(false\;\; positive) - z\,(true\;\; positive) \tag{6-3}$$

Values of d' associated with various true positive and false positive rates are provided in Table 6.1. The d' measure is independent of the criterion adopted by the surveyor, thus allowing meaningful comparisons of sensitivity under conditions in which surveyors' criteria may be different. As stated above, surveyors' criteria may vary for a number of reasons. The relative operating characteristic (ROC) relates the probability of a correct detection to that of a false positive as the response criterion is varied (Figure 6.2). It is conventional in signal detection theory analysis to describe performance in terms of the true positive rate ($1-\beta$) and the false positive rate (α). The remaining two response conjunctions, true negatives (or correct rejections) and false negatives ("misses") are simply the complements of the preceding quantities.

6.4 Human Factors and Two Stages of Scanning

According to statistical decision theory, the *a priori* probabilities of the events and the values and costs associated with the outcomes will influence the placement of the criterion, which is a human factors effect. Thus the detection of a signal in a noise background is determined not only by the magnitude of the signal relative to the background (d'), but also by the willingness of the surveyor to report that a signal is present, i.e., the criterion for responding "yes." The criterion depends on two factors: response value/cost and signal probability. If, for example, a Type I error (false positive) entails a significant cost, the observer will position the criterion more conservatively (e.g., criterion C in Figure 6.1); if it is expected that signals will greatly outnumber non-signals, a more liberal placement of the criterion will yield optimal results (e.g., criterion A in Figure 6.1), but at the cost of significant false positives. It is postulated that, in the context of scanning, the Type I and Type II error rates are embodied in the criterion established by the observer for deciding based on instrument response that contamination is present.

The surveyor's decision itself is influenced by a variety of factors, including the relative costs of "misses" and "false positives," and the surveyor's assumptions regarding the likelihood of contamination being present. The principle implication of the signal detection theory perspective for scanning performance is that, in view of the nature of the task, one must consider false positive rate as well as correct detection rate in order to meaningfully characterize human performance. The rewards or penalties associated with various outcomes influence subjects' responses. In the context of scanning surveys, these factors may affect performance significantly. Surveyors are typically motivated to detect all instances of possible contamination, i.e., to maximize the correct detection rate. However, there are costs associated with incorrectly identifying areas as being contaminated (e.g., making follow-up static measurements or collecting and analyzing samples). The placement of the criterion reflects a balance between these two influences. Observers' estimates of the likelihood/frequency of signals will also influence their willingness to decide that a signal is present. Other things being equal, then, a surveyor will adopt a less-strict criterion when examining areas in which contamination may be expected. Similarly, surveyors' criteria may be more strict when examining areas in which they don't expect contamination to be present. The nature of this decision process is considered in more detail below.

In practice, surveyors do not make decisions on the basis of a single indication. Rather, upon noting an increased number of counts, they pause briefly and then decide whether to move on or take further measurements. Thus, scanning consists of two components: continuous monitoring and stationary sampling. In the first component, characterized by continuous movement of the probe, the surveyor has only a brief "look" at potential sources, determined by the scan speed. The surveyor's criterion (i.e., willingness to decide that a signal is present) at this stage is likely to be liberal, in that the surveyor should respond positively on scant evidence, since the only "cost" of a false positive is a little time. The second component occurs only after a positive response was made at the first stage. It is marked by the surveyor interrupting his scanning and holding the probe stationary for a period of time, while comparing the instrument output signal during that time to the background counting rate. Owing to the longer observation interval, sensitivity is relatively high. For this decision the criterion should be more strict, since the cost of a “yes” decision is to spend considerably more time taking a static measurement or sample. If the observation interval is sufficiently long, an acceptable rate of source detection can be maintained despite application of the more stringent criterion. For example, the solid line in Figure 6.2 represents performance for a 4-second observation. Under these conditions, roughly 95% correct detections can be achieved with only 10% false positives.

Owing to the fact that scanning can be divided into two stages, it is necessary to consider the surveyor’s scan sensitivity for each of the stages. Typically, the MDCR associated with the first scanning stage will be greater due to the brief observation intervals of continuous monitoring—provided that the length of the pause during the second stage is significantly longer. Typically, observation intervals during the first stage are on the order of 1 or 2 seconds, while the second stage pause may be several seconds long. The greater value of MDCR from each of the scan stages is used to determine the scan sensitivity for the surveyor.

6.5 The Ideal Observer Paradigm

In addition to allowing surveyors’ sensitivity to be evaluated independently from their decision criteria, signal detection theory also allows their performance to be compared to that of an ideal observer. In this section, an ideal observer approach to detection in the context of radiological scans is outlined, and the results of relevant laboratory findings are summarized.

If the nature of the distributions underlying a detection decision can be specified, it is possible to examine the performance expected of an ideal observer, i.e., one that makes optimal use of the available information to achieve a specified goal (e.g., to maximize the percent correct responses). This is of interest in the present context because it allows the basic relationships among important parameters (e.g., background rate and length of observation) to be anticipated, and it provides a standard of performance (actually an upper bound) against which to compare performance of actual surveyors.

The audio output of a survey instrument represents randomly occurring events. It will be assumed that the surveyor is a “counting” observer, i.e., one that makes a decision about the presence or absence of contamination based on the number of counts occurring in a given period of time. This number will have a Poisson distribution, and the mean of the distribution will be greater in the presence of contamination than when only background activity is present. When the intensity of activity associated with contamination is low, as it often is during final status surveys, these distributions will overlap. The ideal observer decides that contamination is present if the number of counts is greater than x, where the criterion value x is chosen to maximize percent correct. NUREG/CR-6364 describes the process by which the performance expected for an ideal observer (in terms of correct detection and false positive rates) can be determined from tabled values of the cumulative Poisson distribution.

If acceptable performance (in terms of true and false positive rates) can be specified, the source levels required to support such performance for the ideal observer can be estimated. Section 6.7

provides the calculation approach for determining the MDCR for the ideal observer. It can be shown (Egan 1975) that the MDCR would be expected to be proportional to the square root of the number of background counts. Thus, the minimum detectable net source is a multiple of the background level at count rates typical for GM detectors, and a fraction of the background level at count rates typical for gas proportional and NaI scintillation detectors.

6.6 Actual Surveyor Performance - Field Tests and Computer Simulations

The performance of surveyors conducting scans was examined under field conditions and using computer simulations. As described in the previous section, signal detection theory offers a means of understanding the constraints on human performance in such tasks. This section describes the methods and results of field studies designed to assess the performance of surveyors working under conditions that were reasonably close to those encountered in actual surveys but that nevertheless allowed performance measures to be collected. Laboratory studies using simulated sources and backgrounds are summarized—complete descriptions of the methodology and analysis of results are provided in NUREG/CR-6364. These studies quantified the abilities of surveyors under more controlled conditions.

6.6.1 Field Tests of Surveyor Performance

Scan surveys were conducted under controlled conditions to examine the abilities of surveyors to detect typical source configurations in circumstances that approximated those encountered in the field. Both indoor and outdoor field scan tests were conducted using standard survey instruments for scanning.

6.6.1.1 General Methodology of Field Tests

Experiments were designed and analyzed in accord with the human factors considerations developed previously. Specifically, the surveyors' behavior during the scanning surveys was recorded in a way that allowed both components (continuous and stationary) of the scanning activity to be examined, and an analysis was used which allowed both true positive and false positive rates to be estimated. As a result, it was possible to describe the scanning process (rather than just the result), and to make meaningful performance comparisons among surveyors and among conditions.

The true positive rates for the continuous and the stationary components of the scanning task were determined by dividing the number of sources to which one or more positive responses were made by the number of radioactive source configurations. For the continuous scanning component, a pause in the movement of the probe was considered a positive response. A response was considered to have been associated with a source if it fell within any of the areas of elevated activity as mapped before the start of the field trials. (It should be emphasized that positive responses occurred simply by the surveyor pausing at these source locations, even if the surveyor subsequently concluded that the response did not represent a signal above background.) For the stationary component, a positive response was the identification of a location as a source judged to be in excess of background by the surveyor. The number of false positives for the continuous task was computed as the total number of times the surveyor paused minus the number of pauses associated with sources. An estimate of the number of opportunities for a false positive was required in order to compute the false positive rate (refer to NUREG/CR-6364).

The experiments employed actual radioactive sources and scanning instrumentation. Radioactive sources were positioned so that they could not be detected visually by the surveyors. The surveyors were given written instructions (see example, Figure 6.3) and a scale map of the test area to be scanned, and then instructed to perform a 100% scan of the test area at a specified scan rate. Surveyors marked on the map the areas they judged as containing residual activity in excess of background along with the actual meter reading (in cpm) for those areas. While the surveys were being conducted, observers recorded on a similar map any locations at which the surveyor briefly paused.

The indoor experiments consisted of performing scans for beta activity on an interior wall at a height of 0.5 to 2 m with a GM detector (20 cm^2 probe area) and a gas proportional detector (126 cm^2 probe area). The length of the wall section surveyed was 5 m, resulting in a test area of 7.5 m^2. Scale maps of the indoor test area for the GM and gas proportional detector scans are shown in Figures 6.4 and 6.5. In the outdoor experiment, an area measuring 20 m × 30 m was surveyed. Figure 6.6 shows the scale map of the outdoor field test area. The scanning technique for the outdoor field test consisted of swinging the NaI detector from side to side, keeping the detector just above the surface of the ground at its lowest point. Surveyors covered 100% of the test area using lanes 1 m wide at a scan rate of 0.5 m/s. Additional detail concerning the field tests methodology is provided in NUREG/CR-6364.

6.6.1.2 Field Test Results

The field test results are described in NUREG/CR-6364; a few key points are discussed in this section. The analysis of the ideal observer demonstrated that the time for which the activity is sampled determines the information that is available to the surveyor. Thus, if the probe is moved too quickly, the distributions of activity on which the surveyor's decision is based will not be sufficiently distinct to support acceptable performance. This effect may have been the reason for some relatively intense sources going undetected in the outdoor survey. Although the movement of the probes was not directly measured in any of the field tests, differences in technique among surveyors were noted by the observers and probably contributed to apparent differences in sensitivity.

Similarly, surveyors sometimes failed to correctly identify sources at locations they had paused over—this may have been due to the probe being held stationary for too short a time to support a sufficiently high correct detection rate given the strict criterion for a final positive response.

The importance of the surveyor's criterion for pausing the probe was evident from the analysis of the ideal observer. The operating point for the first (continuous) component established the upper bound for correct detection rate, reflecting the need for the criterion to be quite liberal at the first scan stage. The field tests confirmed that surveyors generally do adopt liberal criteria (i.e., they paused often), but the data indicated that there was much variation among surveyors in this regard—correct detections varied greatly with changes in this criterion, especially for difficult-to-detect sources (e.g., the indoor GM survey).

Equally important in determining the minimum detectable concentration is the surveyor's criterion for identifying areas as contaminated. The field tests revealed considerable variation among surveyors—even between surveyors with roughly equal sensitivity. The extent to which surveyor's performance in this case is subject to the assumed likelihood of a source being present, or the frequency of sources being found as the survey progresses, was also unknown.

To summarize, the important points from the field tests are (1) the sensitivity can vary considerably among surveyors, (2) the surveyor's choice of a criterion for a positive response is quite important in determining success in identifying sources—both to the decision to momentarily pause moving the probe and to the final decision regarding the presence of contamination, and (3) although a surveyor's training, experience, and scanning technique may afford adequate sensitivity to detect a given source level, detection performance may not be optimal unless *both* of these decisions are based on appropriate criteria that do not vary significantly over the course of the survey.

6.6.2 Computer Simulation Tests of Surveyor Performance

This section gives a general overview of the computer simulation tests performed to evaluate scan sensitivity—NUREG/CR-6364 provides greater detail of the procedures and results.

A computer simulation of the audio output of a survey device was developed, which allowed audio signals representing various combinations of source and background activity levels to be easily produced. Programming was added to implement a variety of psycho-physical procedures, a user interface to collect surveyor responses, and various scoring and data recording routines. In the simulation tests, three different psychophysical procedures were used in conjunction with the survey simulation. The procedures addressed different aspects of scanning survey performance.

6.6.2.1 Adaptive Procedure

An *adaptive* procedure was used to determine the source intensity needed to support an arbitrarily chosen level of performance (75% correct) under various conditions. The objective was to determine whether the square root relationship predicted on the basis of the analysis of the ideal observer could be used to predict scanning performance. Since background rates encountered in field surveys can vary over a wide range depending on type of equipment used and type of location to be surveyed, a range of background rates was simulated in the experiments. Because detectability (for the ideal observer) is also determined by the length of the observation, various observation intervals were simulated as well.

Results were evaluated for net source levels corresponding to 75% correct performance for detection in backgrounds of 60, 120, 240, 1,000, 3,000, and 6,000 cpm. Similar to the values for lower background rates, the values for 3,000 and 6,000 cpm define a line with a slope of 0.5 on log-log axes; that is, the ‘square root of background’ relationship apparently holds. This indicates not only that the ‘square root relationship’ adequately describes performance at high as well as low background rates, but also that surveyor efficiency does not vary greatly over this range.

The results of the adaptive experiment indicate that if a given source level allows acceptable performance for a certain background rate and probe speed, it is possible to estimate the source level expected to yield equal detectability for other backgrounds and speeds. It should also be noted that, given the high degree of variability in actual performance (within and between individuals), this prediction is of *average* performance.

6.6.2.2 Confidence Ratings Procedure

A detection procedure employing *confidence ratings* was used to determine not only the true and false positive rates associated with a given condition but also the operating characteristic for each surveyor. Results from this procedure allowed a number of aspects of performance to be considered. The data allowed the calculation of independent measures of sensitivity and criterion. The objective was to determine the relationship of actual to ideal performance and to examine differences among surveyors. On the basis of the ROCs derived from the confidence ratings, it was also possible to determine whether a simple signal detection theory model could be used to predict changes in performance associated with changes in criteria.

The surveyors' actual performance as compared with what is ideally possible (given the statistics of the distributions of background and source counts) is an indication of the efficiency of the surveyors. This efficiency can be modeled by assuming that the surveyor, like the survey instrument, does not necessarily register every event. By adjusting the proportion of counts that the ideal observer registers, it is possible to roughly equate the ideal and actual performance. The proportion at which the two most closely coincide can be taken as the efficiency of the surveyor. The efficiencies established by this method for the four surveyors who completed the confidence rating experiment were between 0.5 and 0.75.

6.6.2.3 Continuous Monitoring Procedure

In the continuous *monitoring* procedure, observation intervals were not defined for the surveyor and no feedback was given as to the correctness of responses. The objective was to examine performance under circumstances closer to those characteristic of actual survey scanning. For a given background rate and observation interval length (simulated probe speed), sources were presented at random intervals during data collection sessions. The surveyors' task was to respond (by clicking a button on the computer display) whenever they detected evidence of a source. This was equivalent to the decision to momentarily halt the movement of the probe. Surveyors were then allowed to listen to the simulation for as long as they wished before making a second, yes/no decision regarding whether a source was being simulated. Thus, from the surveyor's point of view, the simulation was a reasonably close approximation of the actual task.

Using the methods discussed in NUREG/CR-6364, an index of detectability (d') was computed for the conditions simulated. Comparison of these results with the expected performance of the ideal observer and with the performance of the actual surveyor in defined-interval detection indicated the "efficiency" of the surveyor under conditions that approximate those of actual survey activity.

Surveyors adopted criteria that allowed them to respond during or immediately after the presentation of 90% or more of the simulated sources. That is, they seemed to respond as they would in the field, pausing often as a means of minimizing the number of sources missed. The proportion of background intervals in which one or more responses were recorded ranged from

0.58 to 0.98. Pauses typically lasted roughly 4 to 5 seconds, although many longer pauses (8 seconds or more) were recorded. Examination of a portion of the yes/no decisions made after the pauses indicated that very few sources were missed at this stage, but the false positive rate was also relatively high (roughly 0.25). As expected, performance in these undefined interval tasks was poorer than that in the defined interval situation for the same background and source intensities.

6.6.2.4 General Discussion

Taken together, the results of the simulation studies indicate the extent to which human limitations and the nature of the scanning task reduce the efficiency of the surveyor relative to an ideal observer. The ideal observer attempting to detect 180 cpm (gross) in a background of 60 cpm (i.e., a source three times background), in a 4-second observation interval, will be capable of correctly detecting the source roughly 91% of the time with about 5% false alarms (determined from tabulated values of the cumulative Poisson distribution). This corresponds to a d' value of roughly 3. In the defined interval rating task, using the same background and source values, a typical surveyor detected about 90% of the sources with a false positive rate of 14% for a d' value of about 2.4. In the undefined interval procedure, under the same conditions, the performance of the same surveyor yielded a d' value of 1.8. This demonstrates that (1) even under ideal circumstances (i.e., with defined observation intervals) humans do not behave as perfect counting devices (i.e., they are less efficient than the ideal observer), and (2) in scanning, where observation intervals are not defined, the efficiency of the surveyor (relative to the ideal observer) declines further.

6.7 Estimation of Scan Minimum Detectable Count Rates (MDCRs)

The changes in detectability as a function of background level and observation interval (as determined in simulation studies using adaptive level adjustment) were consistent with theoretical predictions, i.e., the number of source counts required to yield a constant level of performance was proportional to the square root of the number of background counts in the observation. Therefore, if performance is known to be acceptable for a given background/source condition and observation interval, it is possible to estimate source levels expected to support similar performance under other conditions.

6.7.1 Determination of MDCR and Use of Surveyor Efficiency

If a value is assumed for the surveyor efficiency, the number of source counts required to yield a particular level of performance (specified in terms of d') can be estimated. The surveyors' actual performance as compared with what is ideally possible (given the statistics of the distributions of background and source counts) is an indication of surveyor efficiency. This efficiency can be modeled by assuming that the surveyor, like the survey instrument, does not register every event. By adjusting the proportion of counts that the ideal observer registers, it is possible to roughly equate the ideal and actual performance. The proportion at which the two most closely coincide can be taken as the efficiency of the surveyor. Specifically, the surveyor efficiency is used to adjust both the background and source distributions, effectively degrading the counting information available to the surveyor. On the basis of the results of the confidence rating experiment, this efficiency was estimated to be between 0.5 and 0.75. Interestingly, in the limited study of extended periods of monitoring, there was no evidence of the further decrease in performance that might have been expected owing to either a criterion shift or a loss of sensitivity. It cannot be concluded, however, that such decrements would not occur with other observers under other conditions, and it is probably advisable to assume an efficiency value at the lower end of the observed range (i.e., 0.5) when making MDC estimates.

Egan (1975, p. 182) shows that detectability for Poisson distributions can be expressed as

$$D \approx \frac{s_i}{\sqrt{b_i}} \tag{6-4}$$

where b_i is the average number of background counts in an interval. For background rates, b, in cpm and observation interval length, i, in seconds, $b_i = b(i/60)$. The detectability index (D) is asymptotically equal to d'. The minimum detectable number of net source counts in the interval is given by s_i. Therefore, for an ideal observer, the number of source counts required for a specified level of performance can be arrived at by multiplying the square root of the number of background counts by the detectability value associated with the desired performance (as reflected in d'); i.e.,

$$s_i = d' \sqrt{b_i} \tag{6-5}$$

where the value of d' is selected from Table 6.1 based on the required true positive and false positive rates.

For example, suppose that one wished to estimate the minimum count rate that is detectable by scanning in a background of 1500 cpm. Note that the minimum detectable count rate must be considered for both scan stages—and the more conservative value is selected as the minimum count rate that is detectable. It will be assumed that a typical source remains under the probe for 1 second during the first stage, therefore, the average number of background counts in the observation interval is 25 (b_i = 1500* (1/60)). Furthermore, as explained earlier, it can be assumed that at the first scanning stage a high rate (e.g., 95%) of correct detections is required, and that a correspondingly high rate of false positives (e.g., 60%) will be tolerated. From Table 6.1, the value of d' representing this performance goal is 1.38. The net source counts needed to support the specified level of performance (assuming an ideal observer) will be estimated by multiplying 5 (the square root of 25) by 1.38. Thus, the net source counts per interval, s_i, needed to yield better than 95% detections with about 60% false positives is 6.9. The minimum detectable source count rate, in cpm, may be calculated by

$$MDCR = s_i * (60/i) \tag{6-6}$$

which, for this example, is equivalent to 414 cpm (1914 cpm gross). Table 6.2 provides the scan sensitivity for the ideal observer (MDCR) at the first scanning stage for various background levels, based on an index of sensitivity (d') of 1.38 and a 2-second observation interval. The MDCR for the second scanning stage must now be considered.

The minimum number of source counts required to support a given level of performance for the final detection decision (second scan stage) can be estimated using the same method. As explained earlier, the performance goal at this stage will be more demanding. The required rate of true positives remains high (e.g., 95%), but fewer false positives (e.g., 20%) can be tolerated, so that d' (from Table 6.1) is now 2.48. It will be assumed that the surveyor typically stops the probe over a suspect location for at least 4 seconds before making a decision, so that the average number of background counts in an observation interval is 100 (b_i = 1,500* (4/60)). Therefore, the minimum detectable number of net source counts, s_i, needed will be estimated by multiplying 10 (the square root of 100) by 2.48 (the d' value); so s_i equals 24.8. The MDCR is calculated by 24.8 * (60/4) and equals 372 cpm. Thus, the MDCR is greater at the first stage (414 vs. 372 cpm), and will be used for purposes of estimating the scan MDC, which requires consideration of the surveyor efficiency.

For a less-than-ideal observer, Egan (1975, p. 187) shows that detectability is reduced by the efficiency of the surveyor, p, and becomes

$$D \approx \frac{s_i\ p}{\sqrt{b_i\ p}} \approx \frac{s_i \sqrt{p}}{\sqrt{b_i}} \tag{6-7}$$

The minimum detectable net source counts in the observation interval for the less-than-ideal surveyor (p), again using d' to reflect the desired performance, may be written

$$s_{surveyor,i} = \frac{d' \sqrt{b_i}}{\sqrt{p}} \tag{6-8}$$

To continue with the above example, the minimum source counts needed by a surveyor, $s_{surveyor,i}$, with an efficiency of 0.5, is estimated by dividing 6.9 by $\sqrt{0.5}$ (equals 9.8 counts in 1-second observation interval). Thus the required number of net source counts for the surveyor, $MDCR_{surveyor}$, is 585 cpm (2,085 cpm gross). Remember, based on the limited research conducted in this study, it is advisable to assume a surveyor efficiency value at the lower end of the observed range (i.e., 0.5) when making scan MDC estimates. Note that the term MDCR (without subscript) refers to the performance of the ideal observer, and $MDCR_{surveyor}$ related to the performance of the surveyor.

It should be noted that the detectable count rates estimated as described above will not necessarily be similar (414 vs. 372 net cpm) for the first and second stages of the detection model. (The pause length at which the detectable net source is equal for the two stages depends on the choice of d' for each stage.) When attempting to estimate the minimum detectable count rate for given performance requirements, one should chose the greater of the two MDCR values at each scan stage. Typically, the value associated with the first (scanning) stage will be greater, owing to the relatively brief intervals assumed. It should be noted, however, that if the length of the pause (i.e., the interval assumed for the second stage) is not significantly longer than the interval assumed for the first stage, the MDCR value associated with the second stage will be greater.

6.7.2 Review of Assumptions and Results

As a means of summarizing the development of the method for estimating MDCR, each of the key assumptions and the relevant experimental results will be briefly reviewed below.

The central assumption in the estimation of minimum detectable count rate described in this report is that the minimum detectable increment in the number of counts in an observation varies as a function of the square root of the number of background counts in an observation. This is based on a signal detection theory model of a Poisson (or ‘counting’) observer. The results of the adaptive simulation experiments indicated that the this relationship adequately represents observers' performance over a wide range of background rates. It should be noted, however, that for low background rates there was considerable variability in these results both within and between observers.

It was assumed that observers’ performance could be related to that expected of an ideal observer by an efficiency factor which represents the probability of a count being recorded by the observer's decision process, thus reducing the effective number of background and source counts in the observation. The results of the defined-interval confidence rating experiment indicate that this factor is no greater than 0.75. The monitoring (undefined interval) results, along with human factors literature, suggest that a value of 0.5 is more appropriate in estimating minimum levels detectable in the field.

The use of *d'* to convert performance requirements (desired detection rate and permissible false positive rate) into an index of detectability implicitly assumes that the distributions underlying the observers' performance are normal. As mentioned earlier, the fact that the ROCs resulting from the confidence rating experiments were not markedly asymmetrical indicates that the assumption of normality is acceptable.

Finally, it was assumed that surveyors would employ a lenient criterion for pausing the probe (i.e., pausing often) and a more strict criterion when judging the activity observed during the pause. The results of the field experiments were consistent with this assumption and provided a basis for the true and false positive rates assumed in the sample calculations in the previous section. However, as with the other results, there was considerable variation in surveyors’ performance in the field studies. The values used in the examples were typical of the best-performing surveyors. This brings up the point that, although a surveyor efficiency factor was used to adjust estimates calculated in the previous section, the estimates may still represent ‘ideal’ performance with respect to the criteria adopted by the hypothetical surveyor. It is assumed that the surveyor ‘chooses’ and is able to maintain criteria for both decision stages that will allow a desired overall level of performance to be achieved. Of course, surveyors do not consciously set the precise parameters of their behavior; nor are they necessarily aware of changes in these values as a survey progresses. It should also be recognized that estimates produced as illustrated in this document reflect performance typical of a relatively small number of surveyors.

In addition to providing a basis for estimates of MDCR, the model of survey activity described in the previous section implies an optimal relationship between the lengths of the observations associated with the first and second detection stages, deviation from which will result in poorer overall performance. Experiments in which the movements of the probe are tracked and timed would reveal whether surveyors' actual performance approximates the predicted relationship. Because time limitations (explicit or implicit) are necessarily a part of the survey task, surveyors' relative allocation of time to scanning and pausing when the total time available is limited will have a great influence on their effectiveness.

6.8 Scan MDCs for Structure Surfaces and Land Areas

The survey design for determining the number of data points for areas of elevated activity (as in the MARSSIM guidance) depends on the scan MDC for the selected instrumentation. In general, alpha or beta scans are performed on structure surfaces to satisfy the elevated activity measurements survey design, while gamma scans are performed for land areas. Because of their low background levels, the determination of scan MDCs for alpha contaminants is not generally applicable using the approach described in Section 6—rather, the reader is referred to the MARSSIM manual for an appropriate methodology for determining alpha scan MDCs for building surfaces. In any case, the data requirements for assessing potential elevated areas of direct radiation depend on the scan MDC of the survey instrument (e.g., floor monitor, GM detector, NaI scintillation detector).

6.8.1 Scan MDCs for Building/Structure Surfaces

The scan MDC is determined from the minimum detectable count rate (MDCR) by applying conversion factors that account for detector and surface characteristics and surveyor efficiency. As discussed above, the MDCR accounts for the background level, performance criteria (*d'*), and observation interval. The observation interval during scanning is the actual time that the detector can respond to the contamination source—it depends on the scan speed, detector size in direction of scan, and size of the hot spot. In this context, the size of the hot spot relates to the area of detection defined by the detector-to-source geometry (for instance, a 2-mm^2 point source may produce an effective hot spot area of over 100 cm^2). Therefore, the greater the contamination source effective area, and slower the scan rate, the greater the observation interval. Because the actual areal dimensions of potential hot spots in the field cannot be known *a priori*, it becomes necessary to postulate a certain hot spot area (e.g., perhaps 50 to 200 cm^2), and then to select a scan rate that provides a reasonable observation interval. Finally, the scan MDC for structure surfaces may be calculated as follows:

$$Scan\ MDC = \frac{MDCR}{\sqrt{p}\ \epsilon_i\ \epsilon_s\ \frac{probe\ area}{100\ cm^2}} \tag{6-9}$$

where

ϵ_i = the instrument efficiency, and

ϵ_s = the surface efficiency (refer to Section 5).

As an example, the scan MDC (in dpm/100 cm^2) for Tc-99 on a concrete surface may be determined for a background level of 300 cpm and a 2-second observation interval using a hand-held gas proportional detector (126 cm^2 probe area). For a specified level of performance at the first scanning stage of 95% true positive rate and 60% false positive rate (and assuming the second stage pause is sufficiently long to ensure that the first stage is more limiting), d' equals 1.38 (Table 6.1) and the MDCR is 130 cpm (Table 6.2). Using a surveyor efficiency of 0.5, and assuming instrument and surface efficiencies of 0.36 and 0.54, respectively, the scan MDC is calculated as follows:

$$Scan\ MDC = \frac{130}{\sqrt{0.5}\ (0.36)\ (0.54)\ (1.26)} = 750\ dpm/100\ cm^2 \qquad (6\text{-}10)$$

The scan MDC above may be compared to the static MDC (1-minute count) for the same detector of approximately 340 dpm/100 cm^2 using Equation 3-9.

The scan MDC in the above example may be calculated using a faster scan rate, such that yields only a 1-second observation interval. Assuming other parameters in the example remain constant, the calculation steps are

(1) b_i = (300 cpm)*(1 sec)*(1 min/ 60 sec) = 5 counts

(2) MDCR = (1.38)*(√5)*(60 sec/ 1 min) = 185 cpm

(3) Calculate scan MDC:

$$Scan\ MDC = \frac{185}{\sqrt{0.5}\ (0.36)\ (0.54)\ (1.26)} = 1{,}070\ dpm/100\ cm^2 \qquad (6\text{-}11)$$

The scan MDC may be calculated for a higher background level (400 cpm) and a 1-second observation interval. Assuming other parameters in the example remain constant, the calculation steps are

(1) b_i = (400 cpm)*(1 sec)*(1 min/ 60 sec) = 6.7 counts

(2) MDCR = (1.38)*(√6.7)*(60 sec/ 1 min) = 214 cpm

(3) Calculate scan MDC:

$$Scan\ MDC = \frac{214}{\sqrt{0.5}\ (0.36)\ (0.54)\ (1.26)} = 1{,}230\ dpm/100\ cm^2 \qquad (6\text{-}12)$$

Now consider an example to determine the scan MDC for a GM detector (20 cm^2) that is used to scan a concrete wall potentially contaminated with Tc-99—in a background of 60 cpm and with a

2-second observation interval. Using the same level of performance, i.e., 95% correct detection rate and 60% false positive rate at the first scan stage, Table 6.2 provides an MDCR of 60 cpm. Assuming instrument and surface efficiencies of 0.19 and 0.52, respectively, the scan MDC is calculated as follows:

$$Scan\ MDC = \frac{60}{\sqrt{0.5}\ (0.19)\ (0.52)\ (0.20)} = 4{,}300\ dpm/100\ cm^2 \tag{6-13}$$

Finally, an example for determining the scan MDC for a floor monitor is provided. The scan MDC for a large-area (573 cm^2), gas proportional floor monitor may be calculated once a hot-spot area has been postulated. The hot-spot area is necessary not only for the observation interval determination, but also to calculate an appropriate probe area correction. That is, it is typical for the postulated hot-spot size to be less than the floor monitor probe area and, therefore, applying the standard probe area correction of 573 cm^2 /100 cm^2 (equals 5.73) is likely not appropriate. For example, assume that the floor monitor is used to scan a concrete floor for SrY-90 contamination, and the modeled hot-spot area is 100 cm^2 (probe correction factor is unity). Detector parameters include a background level of 1,200 cpm, instrument and surface efficiencies of 0.58 and 0.65, respectively, and a scan rate that yields a 1-second observation interval. The scan MDC is determined for the same level of performance (d' equals 1.38)

(1) b_i = (1,200 cpm)*(1 sec)*(1 min/ 60 sec) = 20 counts

(2) MDCR = (1.38)*(√20)*(60 sec/ 1 min) = 370 cpm

(3) Calculate scan MDC as follows:

$$Scan\ MDC = \frac{370}{\sqrt{0.5}\ (0.58)\ (0.65)\ (1)} = 1{,}390\ dpm/100\ cm^2 \tag{6-14}$$

6.8.2 Scan MDCs for Land Areas

In addition to the MDCR and detector characteristics, the scan MDC (in pCi/g) for land areas is based on areal extent of the hot spot, depth of the hot spot, and the radionuclide (i.e., energy and yield of gamma emissions). If one assumes constant parameters for each of the above variables, with the exception of the specific radionuclide in question, the scan MDC may be reduced to a function of the radionuclide alone. It is generally assumed that NaI scintillation detectors are used for scanning land areas.

An overview of the approach used to determine scan MDCs for land areas follows. The NaI scintillation detector background level and scan rate (observation interval) are postulated, and the MDCR for the ideal observer, for a given level of performance, is obtained. A surveyor efficiency is selected, and then it is necessary to relate the surveyor MDCR ($MDCR_{surveyor}$) to a radionuclide concentration in soil (in pCi/g). This correlation requires two steps—first, the relationship between the detector's net count rate to net exposure rate (cpm/μR/h) is established; and second, the relationship between the radionuclide contamination and exposure rate is determined.

For a particular gamma energy, the relationship of NaI scintillation detector count rate and exposure rate may be determined analytically (in cpm per µR/h). The approach was to determine the gamma fluence rate necessary to yield a fixed exposure rate (1 µR/h) as a function of gamma energy. The NaI scintillation detector response (cpm) was then related to the fluence rate at specific energies, considering the detector's efficiency (probability of interaction) at each energy. It was then possible to obtain NaI scintillation detector versus exposure rate for varying gamma energies (Table 6.3). An example using a 2" × 2" NaI scintillation detector is provided for clarity. Assume that the cpm per µR/h is needed for a gamma energy (E_γ) of 400 keV. The relative fluence rate to exposure rate (value has no particular units associated) may be calculated as follows:

$$Fluence\ rate \approx \frac{1\ \mu R/h}{(E_\gamma)\ (\mu_{en}/\rho)_{air}} \approx \frac{1}{(400)\ (0.0296)} = 0.0844 \tag{6-15}$$

where
(μ_{en}/ρ) is the energy absorption coefficient for air and the value used is for 400 keV.

Next, assuming that the primary gamma interaction producing the detector response occurs through the end of the detector (as opposed to the sides), the probability of interaction (P) for a 400 keV gamma may be calculated as follows:

$$P = 1 - e^{(\mu/\rho)_{NaI}\ (x)\ (\rho_{NaI})} =$$
$$1 - e^{(0.117\ cm^2/g)(5.1\ cm)\ (3.67\ g/cm^3)} = 0.89 \tag{6-16}$$

where

$(\mu/\rho)_{NaI}$ = the absorption coefficient for NaI (0.117 cm^2/g at 400 keV) ,
x = the thickness of the NaI (5.1 cm), and
ρ_{NaI} = the density of NaI (3.67 g/cm^3).

Therefore, the relative detector response for this energy is determined by multiplying the relative fluence to exposure rate (0.0844) by the probability of interaction (0.89)—equals 0.0750.

The manufacturer provides a value of 900 cpm per µR/h for this detector for Cs-137. Using the same methodology described above for the Cs-137 gamma (662 keV), the relative detector response was 0.0396. Finally, the cpm per µR/h for 400 keV for this detector is obtained by taking the ratio of the relative detector response at each energy

$$cpm/\mu R/h,\ 400\ keV = (900) * \frac{0.0750}{0.0396} = 1{,}700\ cpm/\mu R/h \tag{6-17}$$

Therefore, once the relationship between the NaI scintillation detector response (cpm) and the exposure rate is known (Table 6.3), the $MDCR_{surveyor}$ (in cpm) of the NaI scintillation detector can be related to the minimum detectable net exposure rate. The minimum detectable exposure rate is used to determine the minimum detectable radionuclide concentration (i.e., the scan MDC) by modeling a specified hot spot.

Modeling (i.e., using Microshield™) of the hot spot (soil concentration) is used to determine the net exposure rate produced by a radionuclide concentration at a distance 10 cm above the source. This position is selected because it relates to the average height of the NaI scintillation detector above the ground during scanning. The following factors are considered in the modeling:

- radionuclide of interest (considering all gamma emitters for decay chains)
- concentration of radionuclide of interest
- areal dimensions of hot spot
- depth of hot spot
- location of dose point (NaI scintillation detector height above the surface)
- density of soil

Modeling analyses were conducted by selecting a radionuclide (or radioactive material decay chain) and then varying the concentration of the contamination. The other factors were held constant—the areal dimension of the cylindrical hot spot was 0.25 m^2 (radius of 28 cm), the depth of the hot spot was 15 cm, the dose point was 10 cm above the surface, and the density of soil was 1.6 g/cm^3. The objective was to determine the radionuclide concentration that was correlated to the minimum detectable net exposure rate.

As an example, the scan MDC for Cs-137 using a 1.5" × 1.25" NaI scintillation detector is considered in detail. Assume that the background level is 4,000 cpm and that the desired level of performance, 95% correct detections and 60% false positive rate, results in a *d'* of 1.38. The scan rate of 0.5 m/s provides an observation interval of 1-sec (based on hot spot diameter of about 56 cm). The $MDCR_{surveyor}$ may be calculated assuming a surveyor efficiency (p) of 0.5 as follows

(1) b_i = (4,000 cpm)*(1 sec)*(1 min/ 60 sec) = 66.7 counts

(2) MDCR = (1.38)*($\sqrt{66.7}$)*(60 sec/ 1 min) = 680 cpm

(3) $MDCR_{surveyor} = 680/\sqrt{0.5} = 960$ cpm

The corresponding minimum detectable exposure rate is determined for this detector and radionuclide. The manufacturer of this particular 1.5" x 1.25" NaI scintillation detector quotes a count rate to exposure rate ratio for Cs-137 of 350 cpm/µR/h (Table 6.3), which is assumed to account for the 662-keV gamma emission from its short-lived progeny, Ba-137m. Although it is recognized that one must account for the resulting gamma energy spectrum incident on the NaI detector (both primary and scattered gamma radiation), the Microshield™ modeling code only considered primary gamma energies when evaluating the buildup from scattered photons. The NaI detector response will be greater during field applications as compared to the calculated detector response because the detector is more efficient at detecting lower energy scattered photons. This situation is anticipated to yield a conservative determination of the detector response and resulting scan MDC estimate.

The minimum detectable exposure rate is calculated

$$\begin{aligned}&\mathit{Minimum\ detectable\ exposure\ rate} = \\ &\qquad \frac{960\ cpm}{350\ cpm/\mu R/h} = 2.73\ \mu R/h\end{aligned} \tag{6-18}$$

Both Cs-137 and its short-lived progeny, Ba-137m, were chosen from the Microshield™ library. The source activity and other modeling parameters were entered into the modeling code. The source activity was selected on the basis of an arbitrary concentration of 5 pCi/g, and converted to the appropriate units as follows:

$$\begin{aligned}&(5\ pCi/g)\ *\ (1.6\ g/cm^3)\ *\ (1\ \mu Ci/10^6\ pCi) \\ &\qquad = 8E{-}6\ \mu Ci/cm^3\end{aligned} \tag{6-19}$$

The modeling code performed the appropriate calculations and determined an exposure rate of 1.307 µR/h (which accounts for buildup). Finally, the radionuclide concentrations of Cs-137 and Ba-137m (scan MDC) necessary to yield the minimum detectable exposure rate (2.73 µR/h) may be calculated as follows:

$$\mathit{Scan\ MDC} = (5\ pCi/g) * \frac{2.73\ \mu R/h}{1.307\ \mu R/h} = 10.4\ pCi/g \tag{6-20}$$

It must be emphasized that while a single scan MDC value can be calculated for a given radionuclide—other scan MDC values may be equally justifiable depending on the values chosen for the various factors, including the MDCR (background level, acceptable performance criteria, observation interval), surveyor efficiency, detector parameters and the modeling conditions of the contamination.

Determination of the scan MDC for radioactive materials—like uranium and thorium—must consider the gamma radiation emitted from the entire decay series. The following example considers the scan MDC for 3% enriched uranium using the same 1.5" × 1.25" NaI scintillation detector as in the previous example. It is assumed that the only variable change from the previous example is that 3% enriched uranium is modeled instead of Cs-137. Thus, the background level is 4,000 cpm, *d'* is 1.38, the observation interval is 1-second and the $MDCR_{surveyor}$ is 960 cpm, assuming a surveyor efficiency of 0.5.

Before the corresponding minimum detectable exposure rate can be determined for the detector and radioactive material decay series, it is necessary to run Microshield™ and determine the count rate to exposure rate ratio (in cpm/µR/h) by considering each of the gamma emissions and their contribution to the total exposure rate. The first step is to determine the source term for 3% enriched uranium. Realizing that, by weight, the ratio of U-235 to total uranium is 3%, and assuming an activity ratio of U-234-to-U-235 of 22—the activity fractions of 3% enriched uranium are 0.179, 0.036, and 0.785, respectively for U-238, U-235, and U-234. The short-lived progeny of U-238, Th-234 and Pa-234m, will also be present at the same activity fraction as U-238 (0.179) and Th-231, the progeny of U-235, will also be present at an activity concentration of 0.036. There are no short-lived progeny in the decay series immediately following U-234.

The source activity was selected based on an arbitrary concentration of 50 pCi/g for total uranium, divided between the uranium isotopes according to their activity fractions and converted to appropriate units for the modeling code. Therefore, the source term entered from the Microshield™ library was as follows:

- U-238 1.43E-5 µCi/cm^3
- Th-234 1.43E-5 µCi/cm^3
- Pa-234m 1.43E-5 µCi/cm^3
- U-234 6.28E-5 µCi/cm^3
- U-235 2.88E-6 µCi/cm^3
- Th-231 2.88E-6 µCi/cm^3

The modeling code performed the appropriate calculations and determined the total exposure rate, with buildup, of 0.1747 µR/h. Additionally, Microshield™ provided the exposure rate for a number of gamma energies associated with the input source term. These data were used to weight the cpm/µR/h value at each energy by the fractional exposure rate to estimate an overall cpm/µR/h value specific to the source term. Specifically,

Energy (keV) (from Microshield™)	Exposure Rate (µR/h)	cpm/µR/h (from Table 6.3)	cpm/µR/h (weighted)
30	9.86E-4	2320	13.1
50	3.30E-4	5320	10.1
60	3.63E-3	5830	121
80	3.95E-3	5410	122
100	2.01E-2	4420	508
150	1.49E-2	2710	230
200	8.83E-2	1890	955
800	6.38E-3	270	9.86
1,000	3.62E-2	200	41.5

Total weighted cpm/µR/h **2,010**

It is interesting to note that about 85% of the NaI scintillation detector's response to 3% enriched uranium is from gamma energies in the 100 to 200 keV range.

Finally, the minimum detectable exposure rate can be calculated using the cpm/µR/h value, as follows:

$$\textit{Minimum detectable exposure rate} = \frac{960\ cpm}{2{,}010\ cpm/\mu R/h} = 0.478\ \mu R/h \tag{6-21}$$

Lastly, the scan MDC for 3% enriched uranium for the conditions stated in this example may be calculated as follows:

$$\textit{Scan MDC} = (50\ pCi/g) * \frac{0.478\ \mu R/h}{0.1747\ \mu R/h} = 137\ pCi/g \tag{6-22}$$

Table 6.4 provides scan MDCs for common radionuclides and radioactive materials in soil. It is important to note that the variables used in the above examples to determine the scan MDCs for the 1.25" × 1.5" NaI scintillation detector—i.e., the $MDCR_{surveyor}$, detector parameters (e.g., cpm/µR/h), and the hot-spot conditions—have all been held constant to facilitate the calculation of scan MDCs provided in Table 6.4. The benefit of this approach is that generally applicable scan MDCs are provided for different radioactive contaminants. Additionally, the relative detectability of different contaminants is evident because the only variable in Table 6.4 is the nature of the contaminant.

Table 6.1 Values of d' for Selected True Positive and False Positive Proportions

False Positive Proportion	True Positive Proportion							
	0.60	**0.65**	**0.70**	**0.75**	**0.80**	**0.85**	**0.90**	**0.95**
0.05	1.90	2.02	2.16	2.32	2.48	2.68	2.92	3.28
0.10	1.54	1.66	1.80	1.96	2.12	2.32	2.56	2.92
0.15	1.30	1.42	1.56	1.72	1.88	2.08	2.32	2.68
0.20	1.10	1.22	1.36	1.52	1.68	1.88	2.12	2.48
0.25	0.93	1.06	1.20	1.35	1.52	1.72	1.96	2.32
0.30	0.78	0.91	1.05	1.20	1.36	1.56	1.80	2.16
0.35	0.64	0.77	0.91	1.06	1.22	1.42	1.66	2.02
0.40	0.51	0.64	0.78	0.93	1.10	1.30	1.54	1.90
0.45	0.38	0.52	0.66	0.80	0.97	1.17	1.41	1.77
0.50	0.26	0.38	0.52	0.68	0.84	1.04	1.28	1.64
0.55	0.12	0.26	0.40	0.54	0.71	0.91	1.15	1.51
0.60	0.00	0.13	0.27	0.42	0.58	0.82	1.02	1.38

Table 6.2 Scanning Sensitivity (MDCR) of the Ideal Observer for Various Background Levels[a]

Background (cpm)	MDCR (net cpm)	Scan Sensitivity (gross cpm)
45	50	95
60	60	120
260	120	380
300	130	430
350	140	490
400	150	550
1,000	240	1,240
3,000	410	3,410
4,000	480	4,480

[a]The sensitivity of the ideal observer during the first scanning stage is based on an index of sensitivity (d') of 1.38 and a 2-second observation interval.

Table 6.3 NaI Scintillation Detector Count Rate Versus Exposure Rate (cpm per μR/h)

Gamma Energy (keV)	cpm per μR/h[a]	
	2" × 2" NaI Detector[b]	1.25" × 1.50" NaI Detector[c]
20	2,200	990
30	5,160	2,320
40	8,880	3,990
50	11,800	5,320
60	13,000	5,830
80	12,000	5,410
100	9,840	4,420
150	6,040	2,710
200	4,230	1,890
300	2,520	1,070
400	1,700	700
500	1,270	510
600	1,010	390
662	900	350
800	710	270
1,000	540	200
1,500	350	130
2,000	260	100
3,000	180	70

[a]Based on normalizing detector response to the cpm per μR/h value provided by manufacturer for Cs-137. The calculational approach is described in the text.
[b]Detector used was Ludlum Model 44-10; manufacturer provided 900 cpm per μR/h for Cs-137.
[c]Detector used was Victoreen Model 489-55; manufacturer provided 350 cpm per μR/h for Cs-137.

Table 6.4 NaI Scintillation Detector Scan MDCs for Common Radiological Contaminants[a]

Radionuclide/Radioactive Material	1.25" x 1.5" NaI Detector		2" x 2" NaI Detector	
	Scan MDC (pCi/g)	Weighted cpm/μR/h	Scan MDC (pCi/g)	Weighted cpm/μR/h
Am-241	44.6	5,830	31.5	13,000
Co-60	5.8	160	3.4	430
Cs-137	10.4	350	6.4	900
Th-230	3,000	4,300	2,120	9,580
Ra-226 (In equilibrium with progeny)	4.5	300	2.8	760
Th-232 decay series (Sum of all radionuclides in thorium decay series, in equilibrium)	28.3	340	18.3	830
Th-232 alone (In equilibrium with progeny in decay series)	2.8	340	1.8	830
Depleted Uranium[b] (0.34% U-235)	80.5	1,680	56.0	3,790
Processed Natural Uranium[b]	115	1,770	80.0	3,990
3% Enriched Uranium[b]	137	2,010	95.7	4,520
20% Enriched Uranium[b]	152	2,210	107	4,940
50% Enriched Uranium[b]	168	2,240	118	5,010
75% Enriched Uranium[b]	188	2,250	132	5,030

[a]Refer to text for complete explanation of factors used to calculate scan MDCs. For example, the background level for the 1.25" × 1.5" NaI detector was assumed to be 4,000 cpm and 10,000 cpm for the 2" × 2" NaI detector. The observation interval was 1 second and the level of performance was selected to yield d' of 1.38.
[b]Scan MDC for uranium includes sum of U-238, U-235, and U-234.

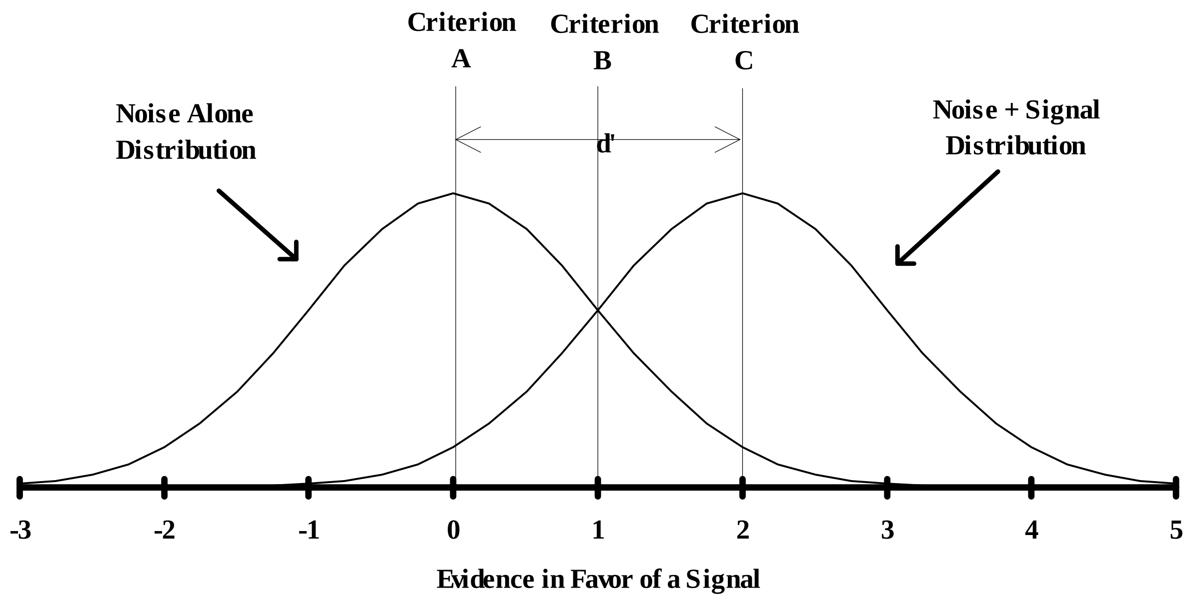

Figure 6.1: Signal Detection Theory Measures of Sensitivity (*d′*) and Critierion Shown Relative to Assumed Underlying Distributions

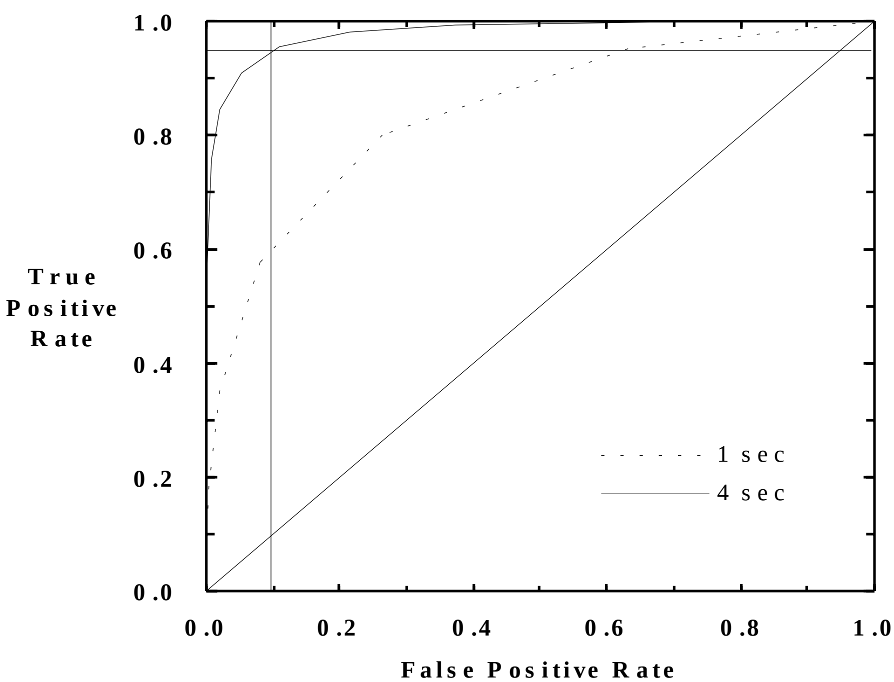

Figure 6.2: Relative Operating Characteristic (Ideal Observer) for Detection of 120 cpm (Net) in a Background of 60 cpm; Observation Intervals of 1 Second and 4 Seconds

Field Determination of Scanning Sensitivity
Survey Instructions

Introduction

Sections of the cardboard are covering radioactive sources that were fastened to the back-side of the cardboard in contact with the wall. Sixteen radioactive sources were randomly positioned on the cardboard in nine discrete configurations. The radioactive sources included C-14, Co-60, Sr-90, Tc-99, Cs-137, and uranium. The radioactive source configurations were prepared to provide varying radiation levels and geometries. The radioactive sources were purposely chosen to emit levels of radiation that are barely discernible above background. Your task is to identify the locations of the areas of direct radiation and record count rate (in cpm) on the provided survey map. You will need a pen and a clipboard to record the results of your survey. Expect to spend 45 to 60 minutes on this exercise.

Specific Tasks

1. Prior to initiating the scan survey, determine the background radiation level of the GM detector the section of cardboard on the wall denoted "Background Check". At this time it is also necessary to compare the cardboard wall with the provided survey map, to ensure that you will record the results on the proper locations on the map.

2. Record the background value of your survey map. Observers will also be recording the results of your scan survey.

3. Put on the headphones and get adjusted to the background counting rate again.

4. Scan the cardboard at a rate of approximately 1 detector width per second (about 5 cm per second with the GM detector), 1 grid section at a time. Instructors will be available to ensure you are scanning at the desired rate. You should keep the detector in contact with the surface during the scan.

5. Listen carefully for an increased click rate above the background count rate.

6. When you think that you have identified an area of elevated direct radiation or "hit", stop and immediately mark that point on your map. Observers will record the number of pauses, even if you can immediately determine that the location was really just a variation of background clicks.

7. Use the following notation when recording the results:

   # Record actual cpm on map for hits.

Figure 6.3 Instructions Given to Field Survey Test Participants for Indoor GM Scans

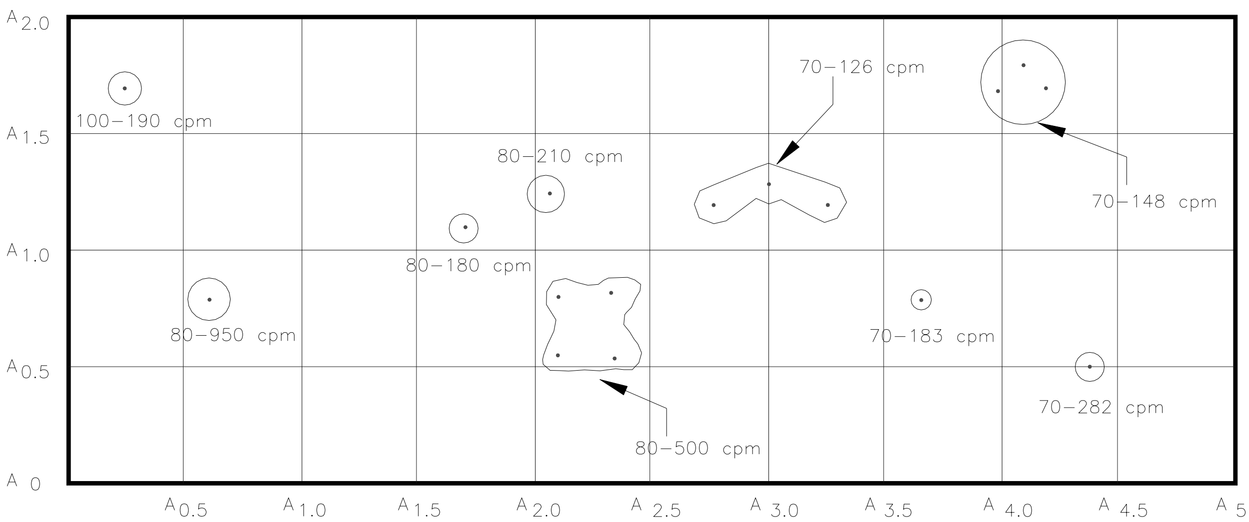

Figure 6.4: Scale Map of the Wall Showing Location, Extent, and Radiation Levels of Hidden Sources for GM Scans

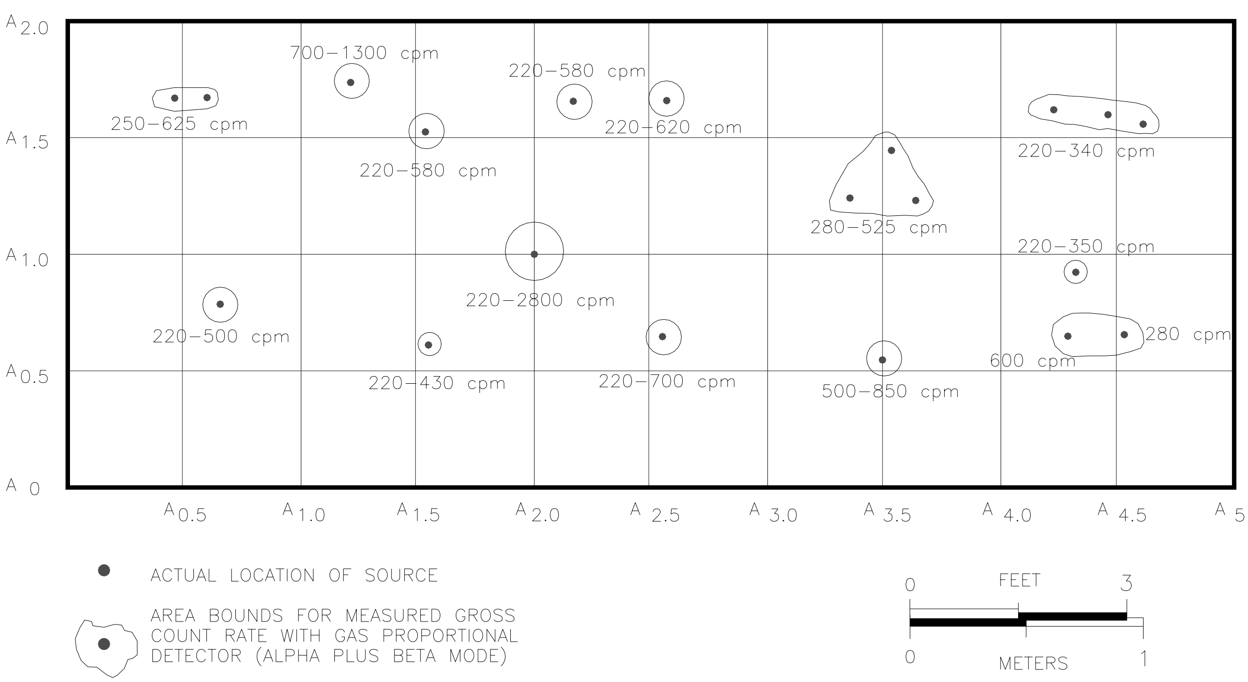

Figure 6.5: Scale Map of the Wall Showing Location Extent, and Radiation Levels of Hidden Sources for Gas Proportional Scans

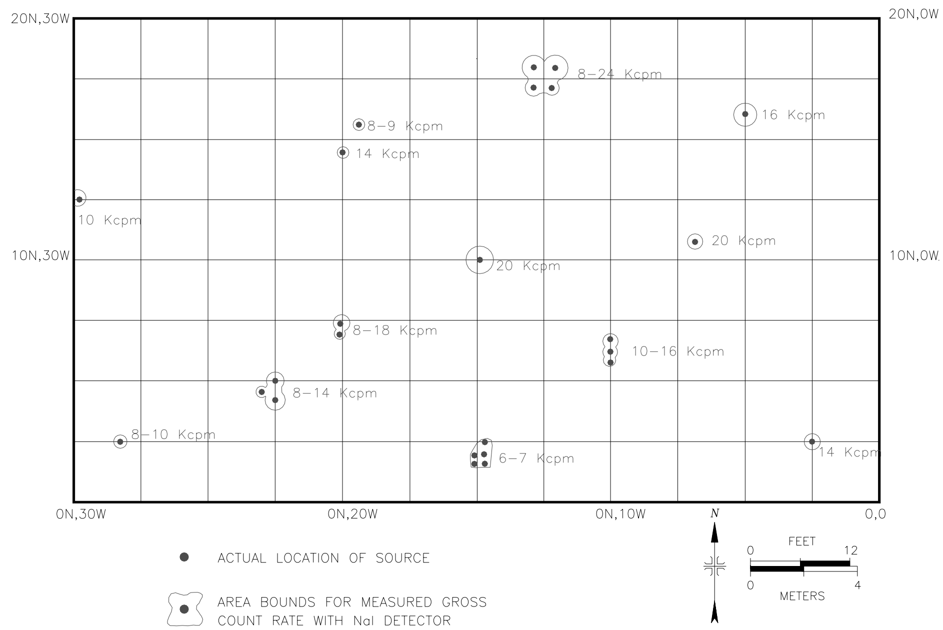

Figure 6.6: Scale Map of the Outdoor Scan Test Area Showing Location Extent, and Radiation Levels of Hidden Sources for NaI Scans